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Comparison of quark jets and gluon jets produced in high energy $e^+ e^-$ annihilations

M E Zomorrodian

Department of Physics, Ferdowsi University, Mashhad, Islamic Republic of Iran

E-mail : zomorrod@science1.um.ac.ir

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Abstract : We report on an experimental comparison of the characteristics of quark induced and gluon induced jets based on an analysis of jet events selected from hadronic events observed at c.m energy of 60 GeV in electron – positron annihilations The mean transverse momentum (P_t) with respect to the jet axis is larger for three jet events than the corresponding value for the two jet events This is in qualitative agreement with the QCD theory which predicts a more chance of gluon radiation in three jet events. Furthermore, the particles in the gluon enriched sample have a higher multiplicity than its counterpart in quark jet sample The ratio of the two multiplicities is 1.3 + – 0 02 This numerical value is in good quantitative agreement with the OPAL experiment Possible explanation for all these features has been presented in this paper

Keywords : jets, quarks, gluons

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1. Introduction

Probably one of the most challenging aspects of high energy hadron interactions is that Quantum chromodynamics (QCD) predicts production cross sections of quarks and gluons, whereas experiments detect instead, jets of hadrons. It is widely believed and there is a large amount of experimental evidence that each jet of hadron originates from a quark, a multi–quark or a gluon jet [1].

QCD has proposed as a theory for the strong interactions. In this theory, the strong force is mediated by the exchange of massless vector gluons between quarks, the fundamental constituents of strongly interacting particles. The coupling of quarks to gluons is expected to decrease with increasing momentum transfer so that in high-Q^2 processes calculations based on perturbation theory are valid. However, in applications of QCD to experimental situations, effects of transition from the unobservable quarks and gluons to the physically observable hadrons (the so-called hadronization process) are unavoidable. This is a complex sequence of low-Q^2 processes for which the techniques of perturbative QCD are not applicable and phenomenological models present a major obstacle to the detailed testing of QCD. It is thus important to obtain experimental insight into the hadronization process using reactions where the primary parton dynamics are well understood.

High-energy $e^+ e^-$ annihilation into three jets of hadrons, which is most simply interpreted as consisting of two quark jets and one gluon jet, provides an opportunity for direct comparisons of the hadronization process for quarks and gluons. Unfortunately, it is extremely difficult to identify the particular parton (*i.e.* quark, multi–quark, or gluon) which is the "parent" of any particular jet. Such a determination would certainly be interesting and would often be useful in comparing theoretical predictions with experiment.

In QCD, gluons have a color factor that is larger than that of quarks by a factor of 9/4, leading one of expect gluon jets to differ from quark jets of the same energy [2]. In particular, the higher color factor should result in gluons radiating more soft gluons, and thus fragmenting into more particles, resulting in softer and fatter jets [3].

We report on an experimental comparison of the characteristics of quark – induced and gluon induced jets based on an analysis of jet events selected from hadronic events observed at c.m energy of 60 GeV. We describe the experimental procedure in Section 2 followed by analysis technique in Section 3. In Section 4, we present our physics results, and finally Section 5 includes the conclusions and discussions.

2. Experimental procedure

The AMY detector (Figure 1) consists of a tracking detector and shower counter inside a 3-T solenoid magnetic coil which is surrounded by a steel flux return yoke followed by a muon detection system. The charged–particle tracking detector consists of a 4 layer cylindrical array of drift tubes (inner tracking chamber, or ITC) and a 40 – layer cylindrical drift chamber (central drift chamber, or CDC) with 25 axial layers of wires and 15 stereo layers. Charged particles are detected efficiently over the polar angle region $\cos\theta$ with a momentum resolution $\frac{\Delta P_T}{P_T} = 0.7\% \times [P_T(Gev/c)]$. Radially, outside of the CDC is a 15-radiation-length cylindrical electromagnetic calorimeter (barrel shower counter, or SHC) which serves as a photon detector. The detector fully covers the angular region $\cos\theta < 0.73$. Selection of multihadron final states from e^+e^- annihilation was based on the charged particle momenta measured in the CDC and on the neutral–particle energy measured in SHC [4]. Further details may be found in Ref. [5].

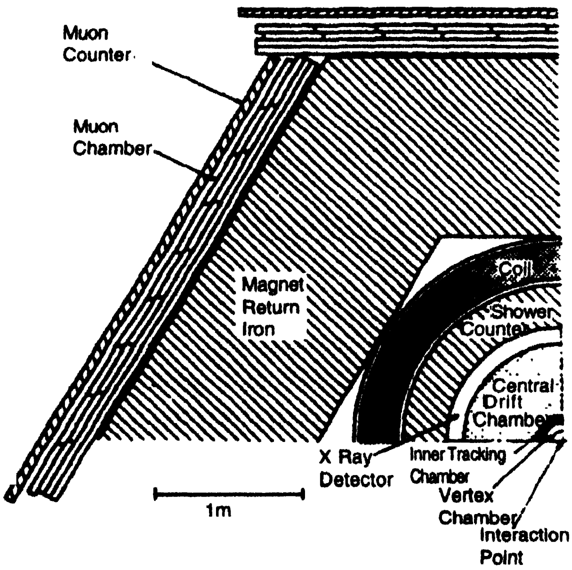

Figure 1. AMY detector.

3. Analysis technique

Jets are formed by means of the jet clustering algorithm introduced by the JADE group [6]. In this algorithm, the scaled mass spread defined as $Y_{ij} = \frac{m_{ij}^2}{E^2}$ with $m_{ij}^2 = 2E_iE_j(1-\cos\theta_{ij})$, is calculated for each pair of particles in the event. If the smallest of the Y_{ij} values is less than a parameter, Y_{cut}, the corresponding pair of particles is combined into a cluster by summing the four momenta. This process is repeated, using all combinations of clusters and remaining particles, until all the Y_{ij} values exceed Y_{cut}. The clusters remaining at this stage are defined as the jets. We use $Y_{cut} = (9\text{ GeV})^2/S$ which is also the case for Ref [6]. S is the square of c.m energy. In our analysis, both charged and neutral particles have been taken into account.

The jets are ordered according to the angles between jets. Jet-1 is defined as the jet opposite to the two jets that have the smallest opening angle, jet-3 is opposite to those with the largest opening angle. Since gluon radiation is a brehmstrahlung - like process, the gluon is typically emitted close to one of the quarks and is usually the lowest energy parton in the final state. Thus it is expected that the jet-3 sample will be gluon enriched relative to the jet-1 and jet-2 samples, which are expected to be quark enriched. Accordingly, we expect in a three jet event, two quark jets and one gluon jet.

4. Physics results

Figures 2 and 3, show separately the cone angular distribution for the two and three-jet data samples respectively. We define the cone angle as the maximum angle between the tracks and the jet axis in each jet. The statistical errors on the average cone angles are also indicated in the figures. There are some different

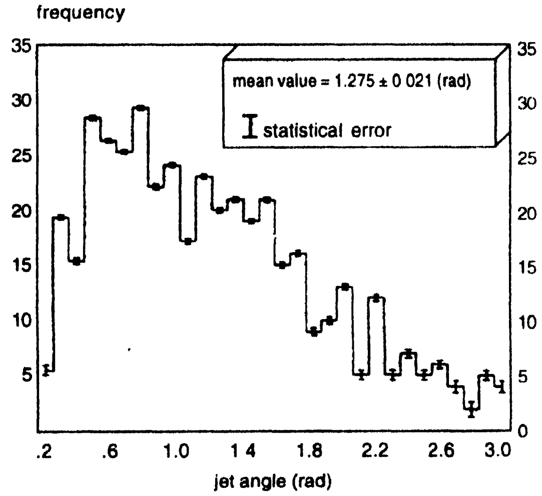

Figure 2. Cone angular distribution for 2-jet events.

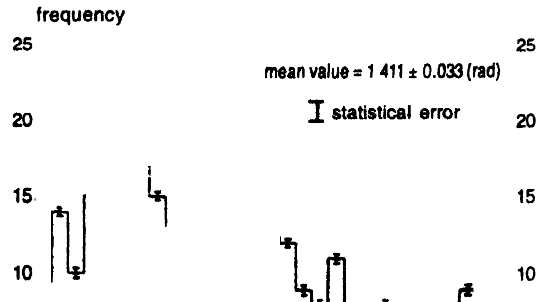

Figure 3. Cone angular distribution for 3-jet events.

characters on this mean opening angle between the two kinds of data. 3-jet events present a wider cone angle than that of 2-jet events. This is due to the fact that the 2-jet events are quark enriched, while 3-jet events contain in addition, one gluon jet. Such an increase in the mean value for the jet angle in 3-jet samples, indicates that the gluon jet spread over a wider angle in space. This also indicates that in quark jets, the energy is concentrated near the jet axis, while in gluon jets, it tends to be diffuse. According to the statistical errors on the average cone angles, our conclusion is still reliable within a few standard deviations.

Figures 4 and 5 show the multiplicity distribution for quark jet and gluon enriched jet respectively. By taking into account the statistical errors on the average values, the figures indicate that within a few standard deviations, the particles in the gluon - enriched jet sample have a higher multiplicity than those particles in quark jet sample. Furthermore, the ratio of the two multiplicities is 1.3 ± 0.02. This numerical value is in a good quantitative agreement with the OPAL results [7].

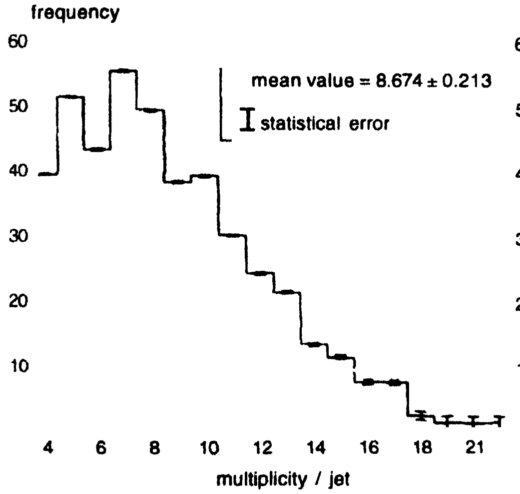

Figure 4. Multiplicity distributions for quark jets.

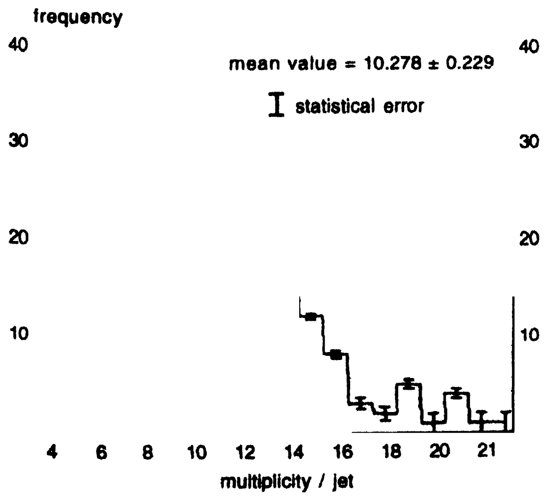

Figure 5. Multiplicity distributions for gluon jets.

Next, we compare the thrust distribution of the gluon jets and the quark jets. Thrust is defined as

$$T = \max \frac{\sum_i |p_{li}|}{\sum p_{li}}$$

The direction of the thrust axis, is that simple axis through the event vertex which maximizes the sum of magnitudes of momentum components of tracks. This is in fact the principle axis of Ref. [8]. In all cases, our variables are defined in overall c.m of $e^+ e^-$ system.

The method used to determine the thrust axis was that employed in other $e^+ e^-$ experiments and which is described by Brandt and Dahmen [8]. This method involves trying as thrust axis all directions defined by the resultant momentum of all multi-body systems in the event. The definition of thrust indicates that the bigger the jet opening angle, the smaller the thrust. Figures 6, 7 illustrate separately the thrust distribution for two and three jets respectively. Furthermore, the average values of thrust together with the statistical errors are added to the figures.

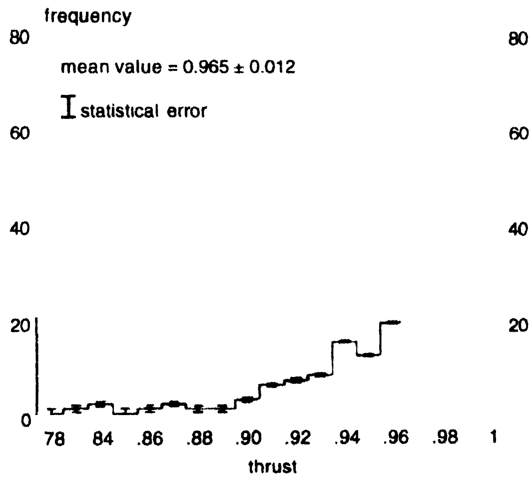

Figure 6. Thrust distribution for quark enriched jets

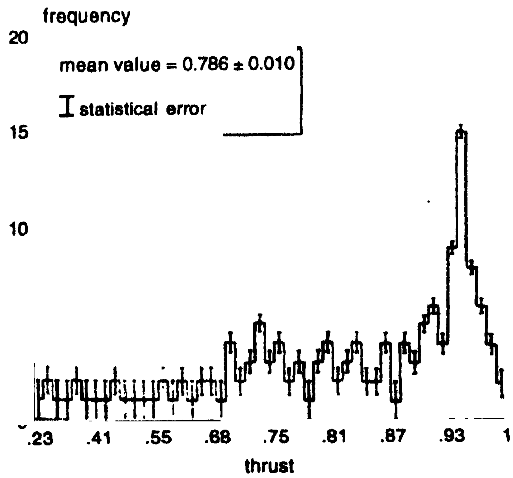

Figure 7. Thrust distribution for gluon enriched jets.

As the figures indicate, the thrust distribution for quark enriched jets shows a peaking towards 100% while the distribution for the gluon–enriched sample is broader. Such behaviour indicates that the mean thrust value for gluon jets is lower than that for quark jets, being also in qualitative agreement with our prediction that the quark jets have a lower opening angle. This conclusion is still reliable if we take into account the effect of statistical errors on the mean thrust values.

Finally, we compare the transverse momentum distribution of quark jets and gluon jets in Figures 8 and 9 respectively. Again we add the statistical errors to the average values. The P_T distribution for quark enriched jets shows more enhancement

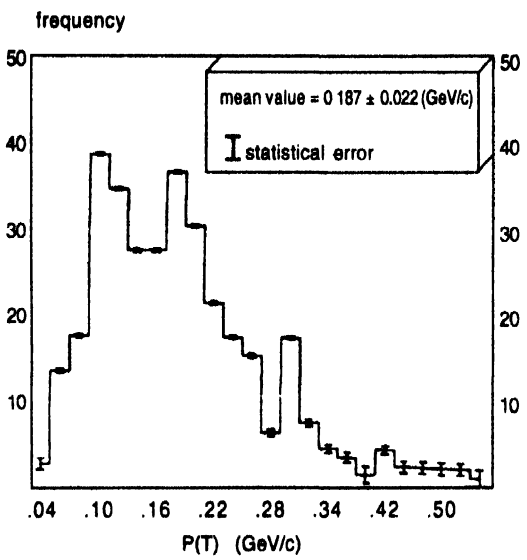

Figure 8. PT distributions for quark jets.

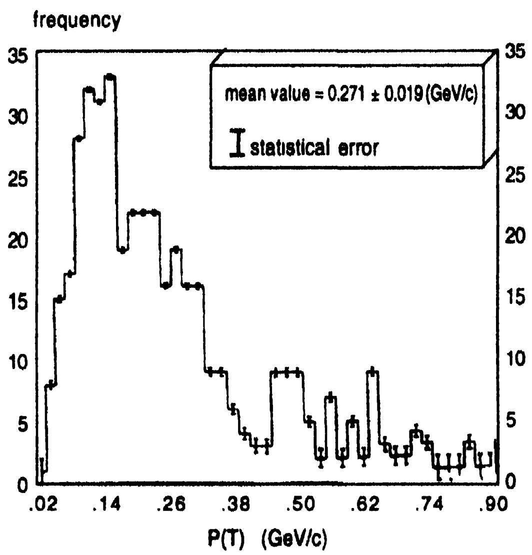

Figure 9. PT distributions for gluon jets.

in the lower values than that for gluon enriched jets. The gluon enriched jets have a broader distribution, leading to a higher average value of P_T for this data. This is again in good agreement with our previous explanation that gluon jets have a larger opening angle, leading to a broader P_T distribution. Inclusion of the statistical errors to the average values also does not affect our conclusions significantly.

5. Conclusions

We have compared the quark induced jets and gluon induced jets, using jet clustering algorithm introduced by the JADE group. We observe that the opening angle for gluon enriched jets is wider than that for quark enriched jets. Thrust distribution for the former is broader than that for the latter. P_T distribution for quark jet shows more enhancement at the lower P_T values than this distribution for gluon enriched sample. Furthermore the mean multiplicity for gluon jets is higher than that for quark jets. The mean values of the above quantities are all larger for gluon jets than those for quark jets within a few standard deviations. Also the above conclusions are all in rather qualitative agreement with the QCD predictions.

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